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DATA REDUCTION AND ANALYSIS FOR THE UNIVERSITY OF CHICAGO CHARGED PARTICLE INSTRUMENT (CPI) ON THE PIONEER 10 AND 11 SPACECRAFT

(NASA/AMES GRANT NAG 2-380)

For the 3 Year Period 1 November 1994 - 31 October 1997

SCIENCE SECTION

PART A

1. INTRODUCTION

This proposal has been prepared in response to the NASA/Ames request for a proposal for support for continued reduction and analysis of data from the University of Chicago Charged Particle Instruments (CPI) aboard the *Pioneer 10* and *11* spacecraft for the period 1 November 1994 - 31 October 1997.

The proposed program of research and analysis is a continuation of investigations that have been carried out at the University of Chicago using the *Pioneer 10* and *11* CPI data over the last several years as the spacecraft continue their exploration of the far outer heliosphere. During the period covered by this proposal *Pioneer 10* will travel from 61 to 69 AU towards of the tail of the heliosphere, observing changes in the far outer heliosphere during the approach to solar minimum, the third solar minimum to have been investigated with Pioneer since launch of the spacecraft. The record of measurements from the *Pioneer 10/11* spacecraft, covering now two 11 year solar activity cycles (one 22 year magnetic cycle) has become fundamental to our understanding of the heliosphere and of its effects on the high energy charged particles accelerated locally or incident from the galaxy. The support requested here will barely enable us to continue our work to radii comparable to the best current estimates of the location of the termination shock. This budget submission with annual limits set by NASA for the first and second year will not enable us to retain our highly trained staff capable of fully exploiting the *Pioneer-10* opportunity.

In previous proposals in this program we have described in detail the analyses that we have undertaken, and have divided the work into separate tasks, each task focused on one of the major scientific objectives or on specific aspects of data processing, archiving, and preparation for analysis. The tasks we have used in the past are summarized in TABLE 1, and they continue to define the broad outlines of our proposed effort. However, because of funding constraints and the changing mix of physical processes available for investigation in the far outer heliosphere, some of these tasks are no longer of first priority in our research or are no longer addressable with current data. Even these tasks, though, continue to yield discoveries and are addressed using data collected during earlier years of the mission for comparison with current observations from the *Voyager* and *Ulysses* spacecraft. Use of data from earlier phases of the solar cycle, or even earlier solar cycles, allows us to investigate, for example, long term trends in solar modulation, dependence of gradients on the sign of the heliomagnetic dipole, etc. which continue to be questions of great interest and importance for our developing understanding of the heliosphere.

In the current proposal, recognizing the changing emphasis of our work, rather than continuing to use the task structure we have in the past we have re-organized our STATEMENT OF WORK (given below) into two broad tasks consisting of:

1) those activities necessary to prepare the data for scientific analysis and for long-term archiving, and:
2) those activities connected with scientific data analysis.

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Within each task, however, there continue to be specific processes and/or problems that are being addressed, and we give a brief description of the current focuses of our research work and of the expected development of the research over the term of this proposal in our STATEMENT OF WORK below.

As a result of the declining power of the RTGs, both *Pioneer 10* and *Pioneer 11* are now in power-sharing mode. The last data from the *Pioneer 11* CPI are most likely to be collected within this calendar year. Data from the *Pioneer 10* CPI are expected to be received throughout the 3-year performance period of this proposal and into mid-1998. Some reduction in processing and analysis costs is expected as a result of the decline in data volume from the CPI. However, the anticipated decline is less than in direct proportion to the decline in data volume since, in the processing, much of the effort involves bookkeeping activities and preparation of standard overview plots that must be done even though there may be large gaps in coverage, and in the scientific analysis greater effort is required to obtain scientifically meaningful results from the reduced data volume, and more effort will be turned to correlative studies with other spacecraft using existing data and to more detailed analysis of data collected earlier in the mission in the light of the new models and hypotheses that have developed since the data were first analyzed and reported.

The budgets for the three years were imposed by NASA and the effects of forced reductions in staff have been included. The Cost Section contains detailed budgets for both tasks for each of the three years covered by this proposal (1 Nov. 1994-31 Oct. 1997).

2. SCOPE OF SCIENTIFIC OBJECTIVES

At the time of selection of our experiments for the Pioneer missions our principal objectives focused on interplanetary/solar/galactic phenomena, including the dynamics of the heliosphere and the solar modulation of the galactic cosmic radiation. Our objectives also included investigation of the magnetosphere of Jupiter.

We note that all of these objectives are being met and that, in addition to our work towards these objectives, we have opened up -- through a series of discoveries -- several new areas of interplanetary and magnetospheric physics which were unanticipated at the time of launching *Pioneer 10* and *11*.

Launched in 1972 and 1973, *Pioneer 10* and *11* are now the longest duration missions in history from which data in the outer heliosphere are being actively collected and analyzed. A record of the intensities over this period of nearly two complete solar cycles as measured at Earth by the *IMP* satellites and at *Pioneer 10* is shown in FIGURE 1, showing the gradual increase of intensity at *Pioneer 10* as it approaches the modulation boundary of the heliosphere, which is still outside the current position of *Pioneer 10*. Indeed, it is one of the major surprises of the *Pioneer* mission that the modulation boundary is so far from the sun, and that the rate of increase of the cosmic ray intensity with radius is so gradual, corresponding to a radial gradient of only ~1%/AU as measured in the most recent data. *Pioneer-10* is the only mission traveling in the direction opposite to *Voyager-1*, *Voyager-2* and *Pioneer-11*.

It is important to recognize the importance of such long running sets of measurements with a single instrument. With the *Pioneer* data it has been possible to carry out heliospheric investigations over a wide range of conditions including:

- the quasi-stable conditions of 1972-77
- the turbulence of increasing solar activity 1978-1981
- a period of moderate maximum solar activity in 1982-83
- a surprisingly dynamic and non-equilibrium state that prevailed at the solar minimum of 1987, when the modulated intensity at 1 AU had already begun to decrease in response to renewed modulation while it was still increasing at *Pioneer 10* in the outer heliosphere

- the strongest solar maximum for which measurements are available from space-based instrumentation which produced, in 1991, the lowest cosmic ray intensity ever recorded both by ground-based and spacecraft instruments
- the current period of recovery towards solar minimum conditions in which, surprisingly, anomalous components are recovering much more rapidly at 1 AU than even high energy cosmic rays measured with the neutron monitor.

Our understanding of the physics of the heliosphere has been greatly affected by these measurements, and they continue to pose a challenge to the increasingly sophisticated and realistic models that are being developed.

The *Pioneer* missions are the most productive to date among all of the more than 30 space experiments from our group in terms of discovery and reshaping of our concepts of the physics of the heliosphere, the magnetospheres of the planets and charged particle acceleration and propagation in interplanetary magnetic fields. Recognizing this, we have established within the University a firmly-based laboratory which anticipates our continuing research in this field based upon Pioneer data through the 1990's. Within our laboratory, the *Pioneer 10/11* measurements are being correlated with measurements from the University of Chicago instruments on the *Ulysses* (Solar Polar) Mission (launched in 1990), and with 1 A.U. baseline measurements from our instruments on *IMP-8*. We also have established collaborative programs in the acquisition of correlative data from other investigative groups, especially:

- Solar wind and interplanetary field measurements from the *Pioneer 10/11* spacecraft
- Charged particle, solar wind, and magnetic field measurements at 1 AU (principally from *IMPs 5,6,7*, and *8* satellites);
- Charged particle, solar wind, and magnetic field measurements from *Voyager 1* and *2* for the study of heliospheric transient and modulation phenomena;
- Solar observational data, including coronal holes, flares, radio and x-ray data, etc.;
- Neutron intensity monitor data, which have provided continuous measurements of the high energy cosmic ray intensity (mainly from the University of Chicago laboratories in Huancayo, Peru and Climax, Colorado), over more than three solar cycles (FIGURE 2). In March of 1991 we opened a new station on the summit of Haleakala on Maui. This new station is now providing measurements essentially equivalent to those from the Huancayo station, whose operation has been effectively terminated by political instability in Peru.

All of the above are used to carry out the interdisciplinary scientific objectives of our work.

A summary of our current scientific objectives is given in the STATEMENT OF WORK below.

3. ACCOMPLISHMENTS DURING THE PERIOD OCTOBER 1991-SEPTEMBER 1994

Our most significant results published, in press, or reported at conferences during the past 3 years (1991-1994) are listed below, together with a list of our publications and conference presentations during this period. A list of discoveries reported in previous years, extracted from our earlier proposals, is given in APPENDIX A.

HYSTERESIS BETWEEN LOW AND HIGH ENERGY COSMIC RAYS NEAR SOLAR MINIMUM

There is an ongoing discussion as to the relative importance between the modulation mechanisms of gradient and curvature drift versus step decreases in cosmic ray intensity caused by large-scale transient merged interaction regions (MIR). Theory suggests that there is a difference between modulation via drift and MIR which should be solar cycle dependent and also velocity dependent. In order to test the theories we studied cosmic ray intensity profiles near the solar minimum of 1987. We reported a phase lag between the recovery time of low and high energy cosmic rays. At 1 AU, high energy (2 GeV) cosmic rays recovered ~60 days before low energy (0.2 GeV) cosmic rays, while the phase lag measure at 41 AU by *Pioneer 10* was 9-18 days. This reported phase lag supported the contention that drift, an inherently velocity dependent mechanism, and not modulation by MIR, dominates solar modulation near times of minimum solar activity. The decrease in phase lag with radial distance also supports the claim that drift is dominant near solar minimum even at large radial distances, since protons entering the heliosphere need to drift along the neutral current sheet a lesser distance from the boundary to 41 AU than to 1 AU. This support for the drift mechanism dominating modulation near solar minimum is important for all modeling of the time evolution of cosmic ray intensities.

NON-JOVIAN SOURCE OF RELATIVISTIC ELECTRONS IN THE OUTER HELIOSPHERE

As it moves outward in the heliosphere the Chicago instrument on *Pioneer 10* has been able to monitor the 2-30 MeV electron fluxes. Earlier work using these fluxes established that Jupiter is the dominant source for low energy relativistic electrons in the inner heliosphere. By extending the electron measurements through the end of 1988 we were able to determine that the electron flux decreases as one moves radially outward through the heliosphere until it reaches a minimum level near ~25 AU. Beyond 25 AU there is an increase in the electron fluxes and a change in the electron spectrum, both of which are inconsistent with a Jovian source of electrons (see FIGURE 3).

We modeled two possible sources for this new component of 2-30 MeV electrons. It is possible that the increase seen beyond 25 AU represents the appearance of low energy galactic electrons whose flux intensity nearer the modulation boundary has risen high enough to be detectable above background. Another possibility is that these electrons are Jovian electrons which are re-accelerated at the solar wind termination shock and then diffuse inward from the shock position. The second interpretation suggests that continued study of these electrons can lead to useful information about the location of the termination shock.

TESTS FOR POSSIBLE PRESENCE OF AN ANOMALOUS HYDROGEN COMPONENT

The source of the anomalous components is generally thought to be from neutral gas in the local interstellar medium (LISM) which enters the heliosphere and becomes ionized, either through charge exchange or ultraviolet photo-ionization. Anomalous components of helium, nitrogen, oxygen, neon and argon - all of which have high first ionization potentials and should exist as neutral gas - have been reported. However, there has been no definitive report of anomalous hydrogen which also has a high first ionization potential and is known to constitute ~90% of neutral gas in the LISM. In order to address the question of anomalous hydrogen we calculated the deuterium/proton ratio. Since there is no neutral deuterium in the LISM there should be no anomalous deuterium, thus time changes in the deuterium/proton ratio should reflect the relative amount of anomalous hydrogen at various times in the solar cycle. Unfortunately the level of solar modulation also changes with time and thus this will affect the deuterium/proton ratio. Within error, our measurements of changes in the deuterium/proton ratio can be fit using only changes in modulation; however, the data are much better fit by assuming that ~40% of neutral hydrogen in the LISM enters the heliosphere to become anomalous hydrogen. The mounting evidence that there is an anomalous hydrogen component is important in discussions of the termination shock since the anomalous component of cosmic rays is thought to be accelerated there.

PUBLICATIONS AND CONFERENCE PRESENTATIONS USING PIONEER 10/11 CPI OBSERVATIONS 1991-1994:

Refereed Publications

Lopate, C. and J. A. Simpson, The Physics of Cosmic Ray Modulation: Heliospheric Propagation during the 1987 Minimum, *J. Geophys. Res.*, **96**, 15877, 1991.

R. B. McKibben, J. J. Connell, C. Lopate, J. A. Simpson, and M. Zhang, Cosmic Ray Modulation in the 3-D Heliosphere, *Proc. ESLAB Symposium #28, The High Latitude Heliosphere*, to be published *Sp. Sci. Rev.*, 1994.

Published Conference Proceedings:

Lopate, C., Jovian and Galactic Electrons (2-30 MeV) in the Heliosphere from 1 to 50 AU, *Proc. 22nd Int'l. Cosmic Ray Conf. (Dublin)*, **2**, 149, 1991.

Lopate, C. and R. B. McKibben, The 2H/1H Ratio as a Test for the Presence of Anomalous Protons at Pioneer 10 near Solar Minimum in 1987, *Proc. 22nd Int'l. Cosmic Ray Conf. (Dublin)*, **3**, 390, 1991.

Lopate, C., R. B. McKibben, and J. A. Simpson, Radial Gradients of Galactic Cosmic Rays and Anomalous Components in the Heliosphere: Pioneer 10/11, Ulysses, and IMP-8 Measurements, *Proc. 22nd Int'l. Cosmic Ray Conf. (Dublin)*, **3**, 378, 1991.

Lopate, C. and J. A. Simpson, Cosmic Ray Heliospheric Propagation During ~22-Year Solar Magnetic Field Cycles, *Proc. 22nd Int'l. Cosmic Ray Conf. (Dublin)*, **3**, 493, 1991.

Lopate, C., and J. A. Simpson, Recent Pioneer-10 and IMP-8 Measurements of the Anomalous Component and the Search for the Termination Shock, *Proc. 23rd Int'l. Cosmic Ray Conf. (Calgary)*, **3**, 415,1993.

Abstracts of Contributed (+) or Invited (*) Presentations at Conferences

* Lopate, C., Jovian Electrons in the Outer Heliosphere: Implications for an Anomalous Component, *Trans. Am. Geophys. Union*, **73** (no. 14, supplement), 245,1992.

* Simpson, J. A., The Anomalous Helium Component in Three Dimensions of the Heliosphere, *Abstracts, Second Pioneer-Voyager Symposium on Energetic Particles and Fields in the Outer Heliosphere*, Durham, New Hampshire, 1994.

+ Connell, J. J., C. Lopate, R. B. McKibben, and J. A. Simpson, The Deuterium/Proton Ratio as a Measurement of Anomalous Hydrogen, *Abstracts, Second Pioneer-Voyager Symposium on Energetic Particles and Fields in the Outer Heliosphere*, Durham, New Hampshire, 1994.

* R. B. McKibben, Cosmic Ray Modulation and the 3-Dimensional Structure of the Heliosphere, in Observations of the Outer Heliosphere, *Adv. in Sp. Research*, **13** (No. 6), 1993.

Other Publications:

J. A. Simpson, Cosmic Radiation: Particle Astrophysics in the Heliosphere, in *Frontiers in Cosmic Physics* (eds: R. B. Mendell and A. I. Mincer), New York Acad. of Sciences Publication, (Vol. 655), 95-137, 1992.